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Dose Response of Field-Grown Tomato to Mixtures of Ozone and Sulfur Dioxide[1]

K.A. SURANO,[2] P.J. TEMPLE,[3] R.G. MUTTERS,[4] G.E. BINGHAM,[5] J.H. SHINN,[2] and J.K. KERCHER[2]

[1] This work, under EPA Agreement 82DX0533, was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48, University of California, Livermore, CA 94550.

[2] Environmental Scientists, Lawrence Livermore National Laboratory, University of California, Livermore, CA 94550.

[3] Assistant Research Botanist, Statewide Air Pollution Research Center, University of California, Riverside, CA 92521.

[4] Research Assistant, Dept. of Botany, University of California, Riverside, CA 92521.

[5] State Climatologist, Utah State University, Logan, UT 84322.

ABSTRACT

A field study to determine the dose response of field-grown tomato (Lycopersicon esculentum Mill.) to ozone (O_3) and sulfur dioxide (SO_2), both singly and in combination, was conducted during the 1981 and 1982 growing seasons in the Central Valley of California. The exposures were realistic in both time series and concentration. No foliar injury was detected, but both ANOVA and step-wise multiple regression analyses showed that yields were reduced significantly by both O_3 and SO_2. No synergism between pollutants was found. Yield reductions occurred as additive functions of the square of the 7-h (0800-1500 PST) seasonal mean O_3 concentration and the 7-h seasonal mean SO_2 concentration for both years. This tomato cultivar appeared relatively resistant to SO_2 exposures and only showed yield declines at high SO_2 concentrations. However, O_3 exposures caused yield reductions even at current ambient concentrations. Yield reductions were 2 to 3 times more severe in 1982 than in 1981 at similar concentrations. The increased susceptibility of tomato to O_3 observed in 1982 was attributed to cooler and more humid climatological conditions during that year.

<u>Additional Index Words:</u> air pollution, yield, O_3, SO_2, <u>Lycopersicon esculentum</u>.

INTRODUCTION

Tomatoes (<u>Lycopersicon esculentum</u> Mill.) are among the 10 most important crops produced in the U.S., with an annual cash value approaching $1 billion. California captures approximately 90% of the process tomato market with over

100,000 ha planted in 1981, a market value of $303 million (D. Shepard, San Joaquin County Agricultural Commissioner's Office, Stockton, CA, personal communication).

Much of California's tomato production is in the Central Valley near San Joaquin County, downwind of the urban/industrial complex around San Francisco Bay. Air pollution from the Bay Area, primarily ozone (O_3), is trapped by a thermal inversion and contributes to the oxidant air-pollution burden already imposed by increased industrialization, urban growth, and agricultural burning in the San Joaquin Valley.

Present oxidant levels may not only be reducing tomato yield in California, but future additional pollutants may act singly, additively, or synergistically to reduce yields even further. Synergism is important with many crop species (Menser and Heggestad, 1966; Applegate and Durrant, 1969; MacDowall and Cole, 1971; Tingey et al., 1973).

Previous studies indicate tomatoes are susceptible to O_3 based on reduced yield with no foliar injury (Legassicke and Ormrod, 1981), foliar injury with no measured yield reduction (Oshima et al., 1975), both foliar injury and yield reduction (MacLean and Schneider, 1976), and foliar injury alone (Clayberg, 1971; Hill et al., 1961; Reinert and Henderson, 1980; Gentile et al., 1971; Reinert et al., 1972; Tingey et al., 1973). Other studies show tomatoes are resistant to sulfur dioxide (SO_2) (Lotstein et al., 1983). Synergistic effects of O_3 and SO_2 have not been shown, but two studies have indicated that the effects of these pollutants in combination are additive (Shew et al., 1982; Heggestad et al., 1981). Differences in cultivar susceptibility to air pollutants have been shown (Clayberg, 1971; Reinert et al., 1972; Gentile et al., 1971; Henderson and Reinert, 1979). However, most of these studies were conducted on potted plants in greenhouses or in controlled environment chambers under exposure regimes unrealistic in both time series and concentrations. In some field studies, plants have been exposed to ambient oxidants with and without additional SO_2 (Legassicke and Ormrod, 1981; MacLean and Schneider, 1976; Oshima et al., 1977a, 1977b; Heggestad et al., 1981). In only one case (Oshima et al., 1977b) have dose response curves been published that relate yield to pollutant exposure.

As part of the National Crop Loss Assessment Network (NCLAN), whose goals are: (1) to develop dose-response functions that relate yields of major agricultural crops to exposure to O_3, SO_2, and their mixtures; and (2) to assess the national primary economic consequences resulting from such exposures (Heck et al., 1982), a field study was conducted during the 1981 and 1982 growing seasons on an important commercial process tomato variety, "Murrieta." This variety accounts for 25 to 32% of the hectarage in San Joaquin County, and has an annual value of $10 million (G. Terry, Tri-Valley Growers, Modesto, CA, personal communication). Fumigations with O_3 and SO_2, singly and in combination, were conducted on tomatoes grown in a field under otherwise normal commercial growing conditions.

MATERIALS AND METHODS

The experimental site was located on the south-central edge of a 160-ha commercial tomato farm in Tracy, CA. Tomatoes were seeded at a rate of 0.6 Kg/ha on 1 June 1981 and 17 May 1982 following tillage. The soil was a CW-capay clay and was shown by an analysis of cores to be well within an optimal range of micronutrients for tomato production. Fertilizer (280 L/ha 8-24-6 N-P-K), nematicide (28 L/ha ethylene dibromide),[6] and herbicide (3.8 L/ha napropamide,[7] 2.8 L/ha pebulate,[8] and 1.9 L/ha trifluralin[9] (1982

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[6] Ethylene dibromide = 1,2-Dibromoethane.

only) were applied into prepared, false furrow 1.7-m beds. Plants were seeded in single rows in 1981 and double rows in 1982. Densities were 12 plants/m in 1981 and 19 plants/m in 1982. Germination occurred on 17 June 1981 and 7 June 1982. Seed rows were then worked into 50-cm beds, cultivated, and side dressed with 120 kg/ha of N as NH_3 on 8 June 1981 and 30 June 1982. The crop received no further cultivation or fertilizer application.

The 40- by 61-m experimental site, with a 9-m buffer zone on all sides, was divided into thirty-two 56-m^2 plots in four east-west rows of eight plots each. The site was bisected by a 9-m field-access strip on which an instrument trailer was located. Each plot contained one open-top fumigation chamber, 3 m in diameter (Heagle et al., 1973, 1979), centered on a single row of tomatoes in 1981 and over a double row in 1982. Partial rows of plants grew within the chambers on the north and south edges, but were treated as buffer rows and were not harvested. In 1981, each plot also contained an associated companion (ambient air) plot, 3 m long, used to evaluate field variability. In 1982, the number of companion plots was increased to 48, and they were spaced evenly across the field.

The plots were furrow irrigated seven times during the season as part of the grower's regular schedule, with water being applied before any plot reached -0.06 MPa soil-water potential as measured by tensiometers. The entire field and experimental site was aerially sprayed with insecticide

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[7] Napropamide = N,N-Diethyl-2-(1-napthalenyloxy) propanamide.

[8] Pebulate - Butylethylthiocarbamic acid S-propyl ester.

[9] Trifluralin = 2,6-Dinitro-N,N-dipropyl-4-(trifluoromethyl)-benzenamine.

[10] Methomyl = N[[(methylamino)carbonyl] oxy] ethanimidothioic acid methyl ester.

(0.5 kg/ha methomyl,[10] 0.5 kg/ha endosulfan[11]) and fungicide (1.0 kg/ha chlorothalonil[12]). To ensure uniform coverage, the chambers were left with the fans off during aerial applications.

The field was sprayed on 4 September 1981 and 27 September 1982 with 4.71 ha ethephon[13] to terminate vegetative growth and to stimulate fruit ripening. Chambers were hand sprayed in 1981 but not in 1982. In both years, harvest took place two weeks after the application of the ripening agent, on 18 September 1981 and 11 October 1982, respectively.

Ozone was produced from compressed oxygen using an O_3 generator (Griffin Technics, Lodi, NJ). Voltage to the O_3 generator was governed manually in 1981 and by an external controller in 1982, based upon ambient O_3 readings taken at canopy height. Ozone-enriched air was then delivered to the chambers using individual flowmeters (Model PR-234, Ralborg Instruments, Monsey, N.Y.) and Teflon distribution tubing. Ozone was produced and delivered daily from 0800 to 1500 PST, except for minor interruptions. Fumigations began on 15 July 1981, two weeks after flower initiation, and 21 July 1982, one week after flower initiation; they were terminated 14 September 1981 and 11 October 1982, respectively.

Sulfur dioxide treatments were achieved by mixing 100% anhydrous liquid SO_2 with compressed air to provide an approximate 20% SO_2-enriched air stream. This gas was also distributed through individual flowmeters and

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[11] Endosulfan = 6,7,8,9,10,10-Hexachloro-1,5,5a,6,9,9a-hexahydro-6,9-methano-2,4,3-benzodioxathiepin 3 oxide.

[12] Chlorothalonil = 2,4,5,6-Tetrachloro-1,3-benzenedi-carbonitrile.

[13] Ethephon = (2-chloroethyl) phosphoric acid.

Teflon distribution tubing. Constant amounts of SO_2 were delivered daily to chambers from 0800 to 1500 PST. Sulfur dioxide fumigations began 18 July 1981 and 27 July 1982 and were terminated 14 September 1981 and 11 October 1982.

Pollutant levels within the chambers were monitored using a multi-value timesharing system (Scanivalve Corp., San Diego, CA). Samples of chamber air were continually drawn (3 L min^{-1}) through 0.5-μm Teflon filters (Nuclepore, Pleasanton, CA), located mid-chamber at canopy height. The samples passed through calibrated Teflon sample lines and were aspirated. Ozone concentrations were measured with 3 UV-absorption monitors (Model 1003-AH, Dasibi Environmental Corp., Glendale, CA). A fourth monitor continuously measured ambient O_3 concentrations (AA). Three pulsed-fluorescence SO_2 analyzers (Model 43, Thermo-Electron Corp., Hopkinton, MA) were arranged in parallel to monitor chamber SO_2 concentrations. A fourth analyzer measured ambient SO_2.

Two of the O_3 analyzers were certified as transfer standards by the California State Air Resources Board in 1981. The SO_2 analyzers were calibrated using NBS (National Bureau of Standards) traceable bottled standards (Scott-Marin, Inc., Riverside, CA). All instruments passed quality-assurance audits by the U.S. Environmental Protection Agency in 1981 and 1982 with excellent ratings. Routine calibrations and adjustments were made on all gas analyzers throughout the season in accordance with NCLAN protocols (Heck et al., 1982).

Data acquisition was performed using a desktop calculator/scanner system (Model 9830/Model 3497A, Hewlett Packard, Palo Alto, CA). The sampling program controlled fumigation start-ups and stops, accessed all gas analyzers, and controlled the sampling position of the multi-valve system. Chamber atmospheres were sampled two times per hour for a 1.5-min period, with a 1-min wait between sampling periods to assure adequate flushing. Data files were generated every 0.5 h and stored on cassette tape. Data were backed up with strip-chart recorders and hard-copy output.

The experiment consisted of five levels of O_3 and six levels of SO_2 in a 5-by-6 randomized factorial design. The control treatment (charcoal-filtered ambient air) was replicated three times. Levels for each chamber were chosen at random in both years, except the 1981 charcoal filtered chambers; they were assigned the same positions in 1982 because of dispensing and sampling line limitations.

The five treatments in 1981 were charcoal-filtered ambient air (CF), non-filtered ambient air (NF), NF + 0.03 μLL^{-1}, NF + 0.05 μLL^{-1}, and NF + 0.07 μLL^{-1}. In 1982, O_3 was added in proportion to ambient concentrations. The five treatments were CF, NF, NF x 1.2, NF x 1.4, and NF x 1.5. The six SO_2 treatments (as 7-h seasonal averages) in 1981 were: CF (0.00 μLL^{-1}), 0.02 μLL^{-1}, 0.03 μLL^{-1}, 0.06 μLL^{-1}, 0.12 μLL^{-1}, and 0.23 μLL^{-1}. In 1982, the SO_2 concentrations were: CF (0.00 μLL^{-1}), 0.03 μLL^{-1}, 0.05 μLL^{-1}, 0.07 μLL^{-1}, 0.12 μLL^{-1}, and 0.23 μLL^{-1}.

Ratings of visible injury were made for all treatments; plant heights were measured; and plant vigor and conditions of foliage were rated visually for each chamber. Diurnal measurements of stomatal conductance and transpiration were taken in selected treatments in 1982 using a steady-state porometer (Model 1600, Licor Inc., Lincoln, NE).

Harvest began the same day each year as commercial harvest of the adjacent field. In 1981, the single 3-m row in the center of each companion plot and chamber was harvested. In 1982, the entire 3-m double row was harvested; however, border rows within the chambers were removed prior to harvest. Tomato plants were cut at soil level, placed in a 100-L plastic-lined can, and shaken to remove the fruit. Fruits were sorted and counted manually using the same color standard employed by commercial harvesters. Data were collected on fresh weight, dry weight, and numbers of marketable green and red tomatoes, and on fresh and dry weights of foliage, including all stems and leaves. Aliquots were used to assess dry weights in all cases.

Analysis of variance (ANOVA) and step-wise multiple regression were used to analyze the harvest data. During both years, salt accumulation and *Verticillium* wilt severely impacted the yield of some plants within the experimental plot. The plots that were affected in 1981 were a control, NF O_3/0.02 SO_2 and NF + 0.07 O_3/0.23 SO_2. In 1982, the affected plots were a control and CF O_3/0.07 SO_2. Harvest data from these plots were not included in the statistical analyses, but estimates of yields were made following the procedures of Steel and Torrie (1980). Total degrees of freedom in the analysis of variance were adjusted for these estimates. For the ANOVA, the data were analyzed as a 2 x 5 x 6 factorial experiment in a randomized design.

RESULTS

Growing conditions in 1981 were typical of the Central Valley of California, with essentially no deviation from 20-y means. In contrast, the weather in 1982 was cooler and more humid than normal. In 1982, the average maximum temperature of the growing season was 1°C cooler than normal, and the average minimum temperature was 0.5°C cooler. In addition, cooling-degree days were 36% lower, precipitation was more than 0.5 cm greater, cloud cover was greater, and relative humidity was higher than in 1981 (National Oceanic and Atmospheric Administration, 1981, 1982).

Double-row spacing and subsequent higher plant densities in 1982 did not produce significantly higher biomass per unit area. The mean yield of total fruit (fresh weight), based on companion plots, was 67 Mg/ha in 1981 and 64 Mg/ha in 1982. These values were not significantly different, considering the natural variation in the field, and they correlated well with the commercial harvest outside the plots.

Table 1 and Table 2 show seasonal 7-h means, highest hourly mean, second highest hourly mean, and seasonal mean of the daily hourly maximum concentrations for O_3 and SO_2 for 1981 and 1982, respectively. Figures 1 and 2 show representative diurnal curves of seasonal means for 1982 for O_3 and SO_2, respectively. Seasonal 7-h (0800-1500 PST) mean ambient O_3 concentrations were identical for both years and averaged 0.03 μLL^{-1}. Figures 3 and 4 show daily average ambient O_3 concentrations. The ambient SO_2 concentrations were near zero in both years; SO_2 treatment levels were similar in both years, but treatments with O_3 added averaged 43% lower in seasonal mean concentration in 1982 than in 1981. However, as plants were exposed to the added O_3 for 81 d in 1982 and 61 d in 1981, the total seasonal O_3 dose averaged only 24% lower in 1982.

No visible O_3 or SO_2 injury symptoms were observed in either year. Plant height and plant vigor did not correlate with either the O_3 or SO_2 dose.

Total fresh fruit weights of tomatoes from each treatment are given in Table 3. Analysis of variance of these data (Table 4) indicate that yields were significantly reduced by both O_3 and SO_2. The O_3 and SO_2 interaction term was not statistically significant, indicating that the two pollutants acted additively in reducing tomato yield. Stepwise multiple regression analysis supported this conclusion. The most significant independent variable predicting tomato-yield loss in both years was the square of the mean seasonal 7-h O_3 concentration followed by the mean seasonal 7-h SO_2 concentration.

The $O_3 \times SO_2$ term was not significant in either regression equation. Companion plot yields were a significant covariant in 1981 but not in 1982, indicating some field variability in 1981. The companion-plot coefficient was included in the 1981 regression constant by multiplying the coefficient by average companion-plot yield. The best-fit regression equations are given in Table 5.

Tomato yield reductions were two to three times greater in 1982 than in 1981 at comparable O_3 concentrations (Figure 5). Seasonal mean ambient O_3 concentrations were the same in both years, but the regression equations predicted a 3% loss in 1981 and a 6% loss in 1982. At a seasonal mean concentration of 0.05 μLL^{-1} O_3 and zero SO_2, yield losses would be 6% in 1981 and 19% in 1982. Sulfur dioxide by itself had little effect on this cultivar of tomato. No loss in yield was apparent except at seasonal mean concentrations exceeding 0.12 μLL^{-1}. These and other hypothetical yield losses are presented in Table 6.

DISCUSSION

Previous studies have shown tomato yield to be reduced in the field by ambient oxidants. Leggasicke and Ormrod (1981) showed a 30% reduction, Heggestad et al. (1981) a 17% reduction, and MacLean and Schneider (1976) a 33% reduction in total tomato yields as the result of ambient O_3 exposures, when compared to yields under charcoal filtered air. Oshima et al. (1977b) showed a 64% reduction from their most extreme to least extreme ambient condition along a naturally occurring O_3 gradient in Southern California, and a 37% reduction at the midpoint. Comparison of these studies is difficult because of inconsistency in cultivars used, expression of ambient O_3 dose and/or concentration, and reporting of other environmental variables that may influence cultivar response in a specific locality in a given year.

The importance of environmental conditions on the effects of atmospheric pollutants to plants should not be underestimated. Higher humidities can predispose plants to more severe injury, and water stress can cause plants to tolerate higher pollutant exposures (Heck, 1968). The contrast in tomato response to fumigations with O_3 between the two years of this study may be attributable to the seasonal differences in growing conditions in the Central Valley. Under the normal conditions of 1981, evaporative demand was high and the plants experienced some water stress during the hottest part of the afternoon with resulting stomatal closure. Because O_3 was present in the highest concentrations during this same period of the day, the plants may have avoided some O_3 flux into the leaves while responding to the water-stress conditions. In contrast, 1982 had unusually cool, cloudy conditions. With this environment, stomata remained open for longer periods during the day and between irrigations and, therefore, the plants were more susceptible to O_3 injury. Stomatal conductance data (Temple et al., in preparation) support this conclusion. This seasonal environmental effect has also been seen in a cotton/O_3 study in Southern California during the same years (Temple et al., 1985).

For tomatoes, impact varies with regard to cultivar, pollutant exposure, field position, soil conditions, and year (with associated weather variability). To assess accurately the national impact of air pollution on tomato, or any other crop, studies are needed that address this variability. Future studies should be field oriented and should use yield, not foliar injury, as the measure of impact. This idea has been previously suggested by Oshima et al. (1975, 1977a), Clayberg (1971), Tingey et al. (1973), and Legassicke and Ormrod (1981).

CONCLUSIONS

The experiments developed realistic dose-response functions of commercially grown tomatoes exposed to O_3 and SO_2 in the field. Statistical analyses showed that both O_3 and SO_2 reduced yield significantly, but no significant interaction occurred between the two pollutants. Stepwise multiple regression showed that the dose response could be represented as the additive effect of the SO_2 concentration and the square of the O_3 concentration. For both years, the regression coefficients were about the same for SO_2; however, during the moist, cool year of 1982, they increased by a factor of 2.8 for O_3. That only these additive terms were significant in both 1981 and 1982 shows consistency in the dose-response functions between years.

At 1981 and 1982 exposure levels near Tracy, California, we predict that farmers realized a 3 to 6% loss in tomato yield because of existing air pollutants. However, this reduction would be difficult to isolate and observe because normal yield variations of 15 to 19% between fields could mask the O_3 effects unless one could perform an analysis such as that presented here.

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FIGURE CAPTIONS

Figure 1. Diurnal curves of seasonal mean hourly O_3 concentrations for O_3 treatments at Tracy, California, 1982.

Figure 2. Diurnal curves of seasonal mean hourly SO_2 concentrations for SO_2 treatments at Tracy, California, 1982.

Figure 3. Daily 7-h and 24-h ambient O_3 concentrations at Tracy, California, 1981.

Figure 4. Daily 7-h and 24-h ambient O_3 concentrations at Tracy, California, 1982.

Figure 5. Total fruit yield dose response of field-grown tomato to O_3, measured across SO_2 treatments at Tracy, California, 1981 and 1982.

Table 1. O_3 and SO_2 concentrations, 1981 tomato experiment, Tracy, California.

Treatment	Mean[a] concentration	Mean[b] peak	Peak[c] 1	Peak[d] 2
		O_3 ($\mu L L^{-1}$)		
1 (CF)	0.01	0.02	0.04	0.04
2 (NF)	0.03	0.04	0.09	0.09
3 (NF + 0.03)	0.06	0.07	0.11	0.11
4 (NF + 0.05)	0.08	0.09	0.13	0.13
5 (NF + 0.07)	0.10	0.11	0.16	0.16
Ambient	0.03	0.04	0.09	0.09
		SO_2 ($\mu L L^{-1}$)		
1 (CF)	0.00	0.00	0.02	0.02
2	0.02	0.02	0.16	0.14
3	0.03	0.05	0.16	0.14
4	0.06	0.08	0.30	0.30
5	0.12	0.14	0.42	0.38
6	0.23	0.26	0.52	0.50
Ambient	0.00	0.00	0.03	0.02

[a]Seasonal 7-h mean (0800-1500 PST).

[b]Mean daily 1-h peak.

[c]Highest hourly mean.

[d]Second highest hourly mean.

Table 2. O_3 and SO_2 concentrations, 1982 tomato experiment, Tracy, California.

Treatment	Mean[a] concentration	Mean[b] peak	Peak[c] 1	Peak[d] 2
		O_3 ($\mu L L^{-1}$)		
1 (CF)	0.01	0.02	0.08	0.08
2 (NF)	0.03	0.05	0.11	0.10
3 (NF x 1.2)	0.04	0.07	0.14	0.14
4 (NF x 1.4)	0.05	0.08	0.19	0.18
5 (NF x 1.5)	0.05	0.08	0.22	0.21
Ambient	0.03	0.06	0.18	0.18
		SO_2 ($\mu L L^{-1}$)		
1 (CF)	0.00	0.00	0.02	0.02
2	0.03	0.05	0.20	0.18
3	0.05	0.08	0.47	0.25
4	0.07	0.11	0.46	0.40
5	0.12	0.16	0.57	0.51
6	0.23	0.28	0.66	0.59
Ambient	0.00	0.00	0.02	0.01

[a]Seasonal 7-h mean (0800-1500 PST).

[b]Mean daily 1-h peak.

[c]Highest hourly mean.

[d]Second highest hourly mean.

Table 3. Effect of O_3 and SO_2 concentrations on total tomato fresh fruit yield (in Mg/ha), Tracy, California.

Year	SO_2 [a] Conc.	O_3 Concentration[a]				
		0.01	0.03	0.06	0.08	0.10
1981	0.00	62[b]	62	66	55	55
	0.02	73	53[b]	61	49	44
	0.03	71	65	69	56	46
	0.06	51	53	52	50	43
	0.12	68	71	57	57	50
	0.23	43	66	51	52	42[b]
		O_3 Concentration[a]				
		0.01	0.03	0.04	0.05	0.05
1982	0.00	63[c]	59	49	59	47
	0.03	71	57	73	58	43
	0.05	56	54	50	51	46
	0.07	60[b]	56	54	55	49
	0.12	54	61	43	43	53
	0.23	54	55	42	35	47

[a] Seasonal 7-h mean concentration ($\mu L L^{-1}$)(0800-1500 PST).

[b] Estimate.

[c] Average of 2 control chambers.

Table 4. Analysis of variance of total tomato fresh fruit weight, 1981-1982, Tracy, California.

Source	df	SS	MS	F
Year	1	43	43	4.73*
O_3	4	391	98	10.84**
SO_2	5	178	36	3.94*
Year x O_3	4	32	8	0.89
Year x SO_2	5	142	28	3.15*
O_3 x SO_2	20	267	13	1.48
Error	17	153	9	
Total	56[a]			

*Significant at 5% level.

**Significant at 1% level.

[a]Degrees of freedom adjusted for plot estimates.

Table 5. Regression equations and statistics for yields of field-grown tomato (fresh fruit weight), 1981-1982, Tracy, California.

Year	Regression equation	R^2	F
1981	$Y = (-38.8) \times SO_2) - (1702 \times O_3^{\,2}) + 67$	0.67	17.23
1982	$Y = (-38.6) \times SO_2) - (4735 \times O_3^{\,2}) + 64$	0.46	11.33

Y = Yield (Mg/ha).

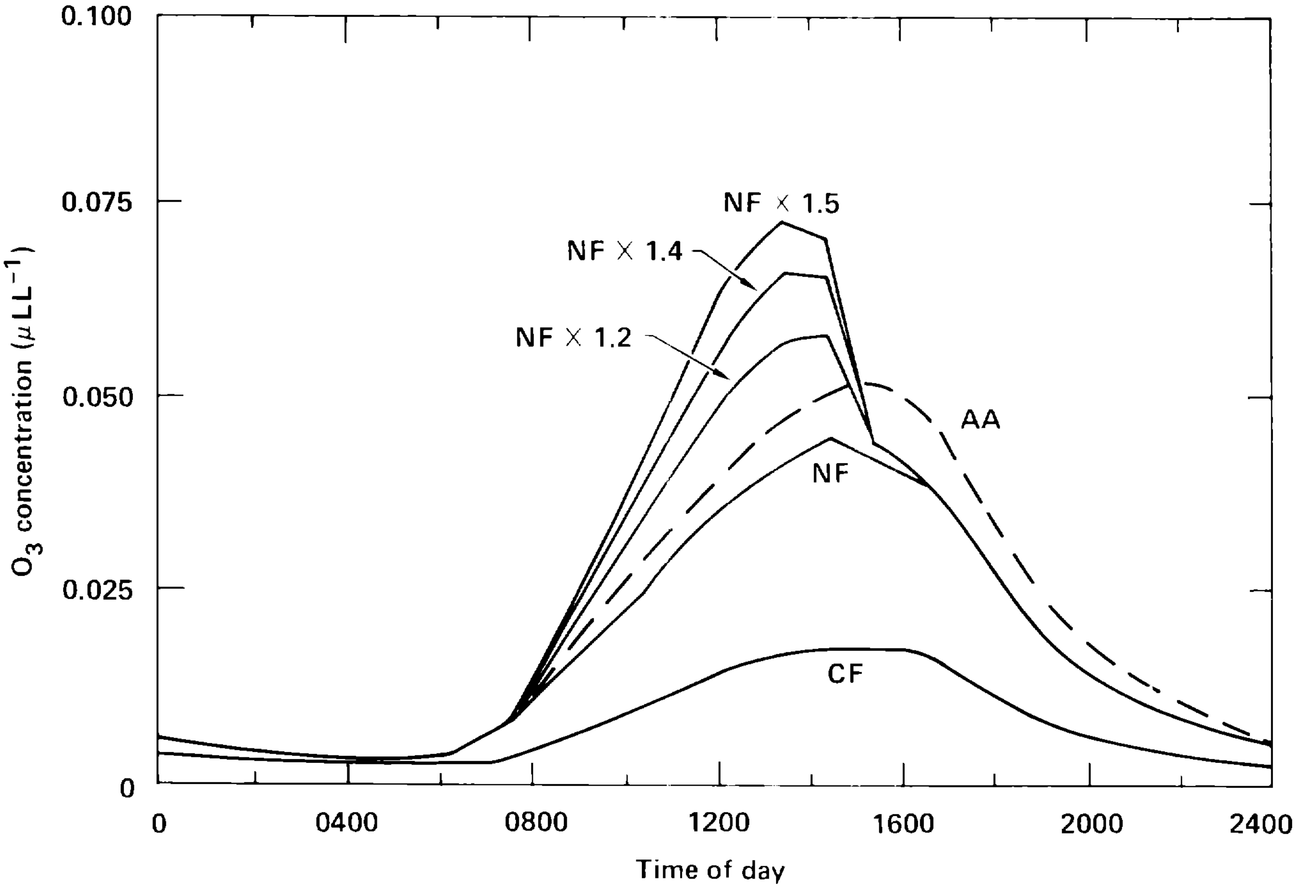
SO_2 = SO_2 seasonal 7-h mean concentration ($\mu L L^{-1}$).

O_3 = O_3 seasonal 7-h mean concentration ($\mu L L^{-1}$).

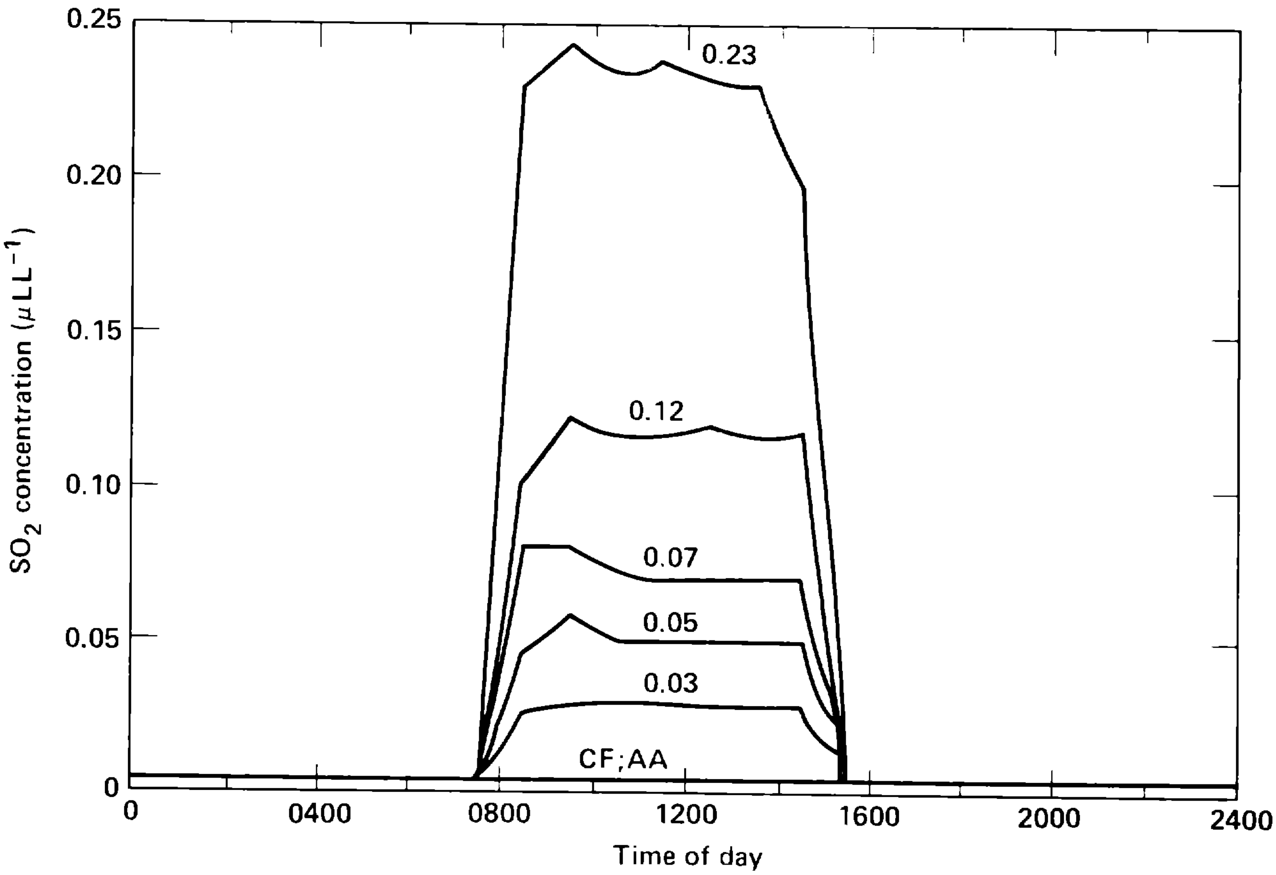
Table 6. Yield reductions in total fresh fruit weight of tomato by combinations of O_3 and SO_2, predicted by regression models.[a]

Year	Average O_3 ($\mu L L^{-1}$)	Average SO_2 ($\mu L L^{-1}$)	Yield reduction (%)
1981	0.03	0.00	3
	0.05	0.00	6
	0.10	0.00	25
	0.03	0.12	10
	0.00	0.17	10
1982	0.03	0.00	6
	0.05	0.00	19
	0.03	0.03	10
	0.00	0.17	10

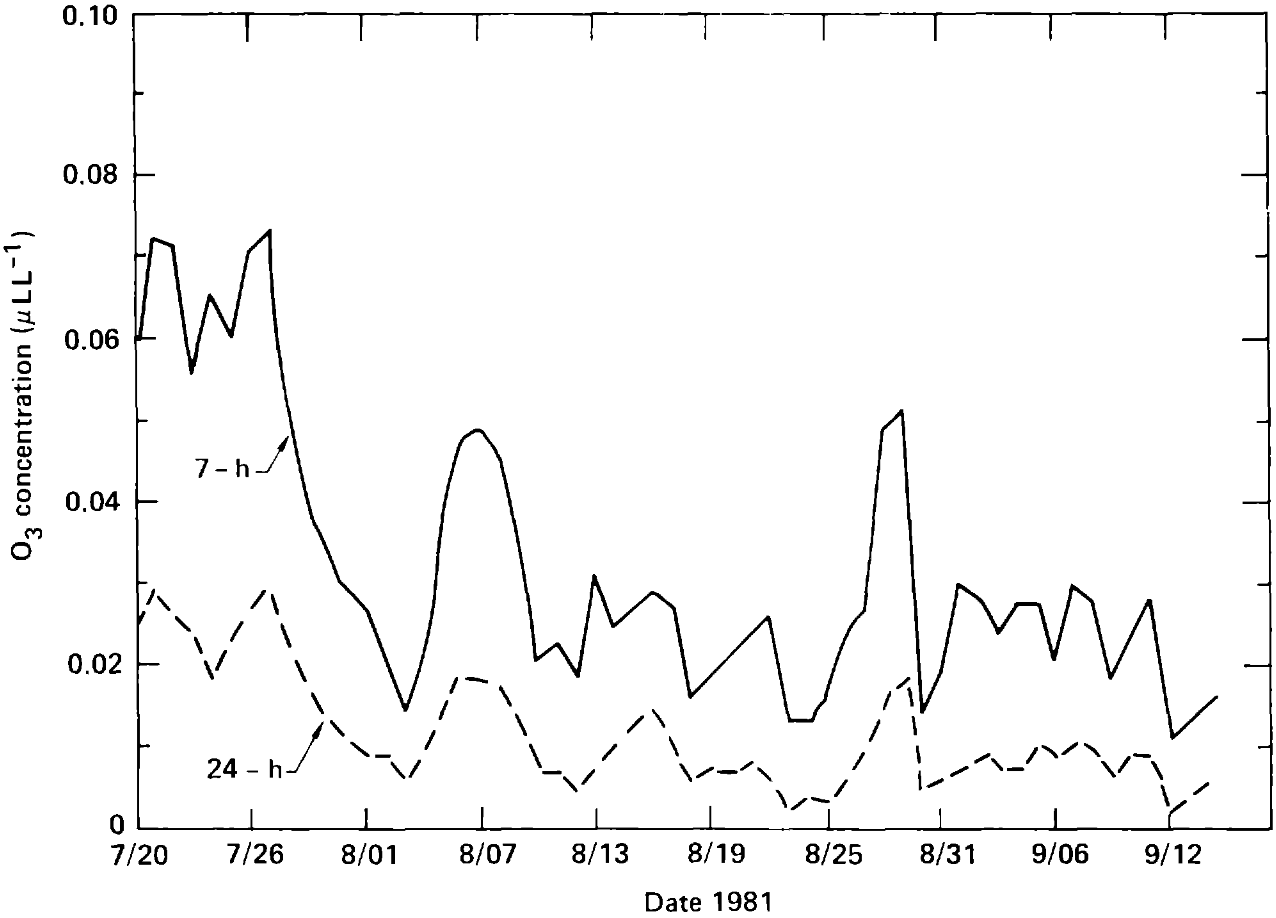
[a]For both 1981 and 1982, ambient O_3 was 0.30 $\mu L L^{-1}$ and ambient SO_2 was 0.00 $\mu L L^{-1}$.



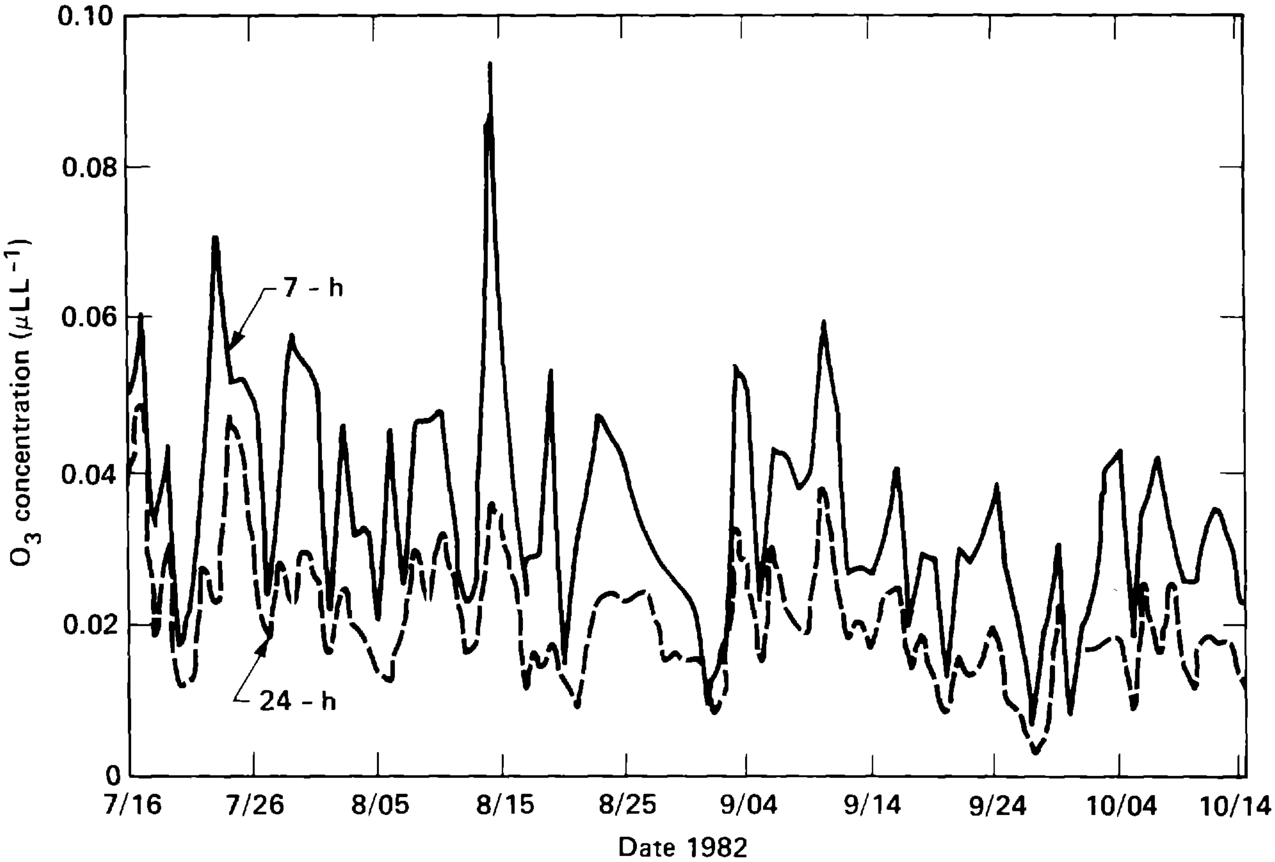
0.100
0.075
0.050
0.025
0
O3 concentration (μLL-1)
0
0400
0800
1200
1600
2000
2400
Time of day
NF × 1.5
NF × 1.4
NF × 1.2
AA
NF
CF

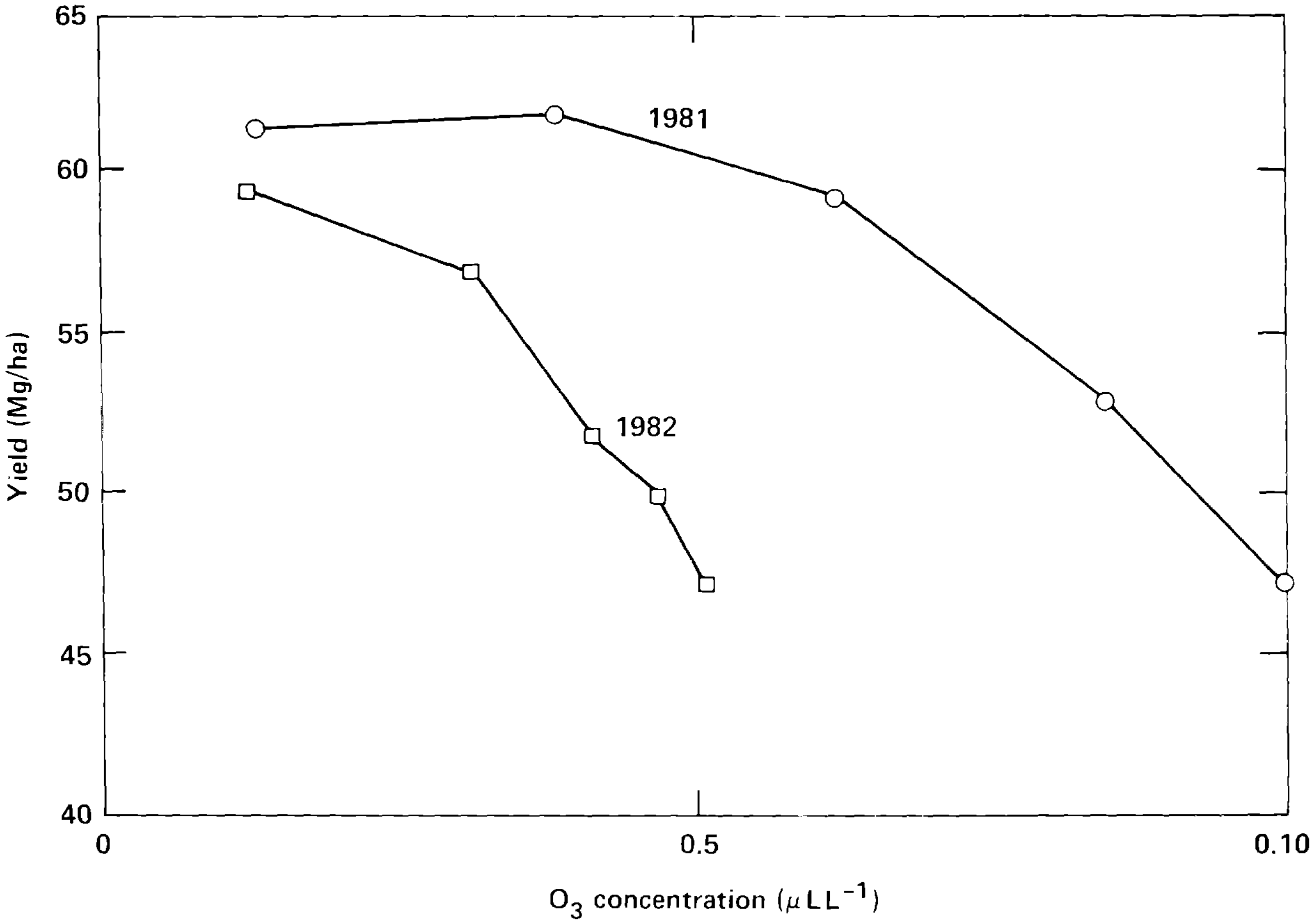


0.25
0.20
0.15
0.10
0.05
0
SO_2 concentration ($\mu L L^{-1}$)
0.23
0.12
0.07
0.05
0.03
CF;AA
0
0400
0800
1200
1600
2000
2400
Time of day



0.10
0.08
0.06
0.04
0.02
0
O_3 concentration ($\mu L L^{-1}$)
7 - h
24 - h
7/20
7/26
8/01
8/07
8/13
8/19
8/25
8/31
9/06
9/12
Date 1981


0.10
0.08
0.06
0.04
0.02
0
O_3 concentration (μLL^{-1})
7 - h
24 - h
7/16
7/26
8/05
8/15
8/25
9/04
9/14
9/24
10/04
10/14
Date 1982



65
60
55
50
45
40
0
0.5
0.10
1981
1982
Yield (Mg/ha)
O_3 concentration ($\mu L L^{-1}$)